Radiation hydrodynamics of tin targets for laser-plasma EUV sources

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Main constituents of the RALEF-2D package

The RALEF-2D code has been developed with the primary goal to simulate high-temperature laser plasmas. Its principal constituent blocks are

1. **Hydrodynamics**
2. **Thermal conduction**
3. **Radiation transport** ← dominates the physics, and the computing resources
4. **EOS and opacities** ← provided by external sources
5. **Laser absorption** ← 3 different models

Equations of hydrodynamics

The **RALEF-2D** code is based on a single-fluid, one-temperature hydrodynamics model in two spatial dimensions (either x,y, or r,z):

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \left(\rho \vec{u} \right) = 0,$$

ideal hydrodynamics

$$\frac{\partial \left(\rho \vec{u} \right)}{\partial t} + \nabla \cdot \left(\rho \vec{u} \otimes \vec{u} \right) + \nabla p = 0,$$

coupling with the radiation field

$$\frac{\partial \left(\rho E \right)}{\partial t} + \nabla \cdot \left[\left(\rho E + p \right) \vec{u} \right] = \nabla \cdot \left(\kappa \nabla T \right) + Q_r + Q_{dep},$$

$$E = e + \frac{u^2}{2}, \quad e = e(\rho, T)$$

$\nabla \cdot (\kappa \nabla T)$ – energy deposition by thermal conduction (local), Q_r – energy deposition by radiation (non-local), Q_{dep} – eventual external heat sources.

Radiation transport

The transfer equation for radiation intensity I_ν in the quasi-static approximation (the limit of $c \longrightarrow \infty$):

$$\boxed{\cancel{\frac{1}{c}\frac{\partial I_\nu}{\partial t}} + \vec{\Omega}\cdot\nabla I_\nu = k_\nu\left(B_\nu - I_\nu\right),} \quad I_\nu = I_\nu\left(t,\vec{x},\nu,\vec{\Omega}\right), \quad B_\nu = B_\nu\left(\nu,T\right)$$

Quasi-static approximation: radiation transports energy infinitely fast (compared to the fluid motion) $\Rightarrow$ the energy residing in radiation field at any given time is infinitely small !

In the present version, the absorption coefficient k_ν and the source function $B_\nu = B_\nu(T)$ are calculated in the LTE approximation.

Coupling with the fluid energy equation:

$$Q_r = -\nabla\cdot\left(\int d\nu \int \vec{\Omega}\, I_\nu\, d\vec{\Omega}\right) = \int_{4\pi} d\vec{\Omega} \int k_\nu\left(I_\nu - B_\nu\right) d\nu$$

Radiation transport adds 3 extra dimensions (two angles and the photon frequency) $\Rightarrow$ **the 2D hydrodynamics becomes a 5D radiation hydrodynamics !**

Not to be mixed up with spectral multi-group diffusion

In many cases the term "radiation hydrodynamics" (RH) is applied to hydrodynamic equations augmented with the multi-frequency diffusion equation

$$\frac{1}{c}\frac{\partial \mathsf{E}_\nu}{\partial t} + \nabla\cdot\left(\mathsf{E}_\nu \frac{\vec{u}}{c}\right) + \frac{1}{3}\mathsf{E}_\nu \nabla\cdot\left(\frac{\vec{u}}{c}\right) = \nabla\cdot\left(\frac{1}{3k_\nu}\nabla \mathsf{E}_\nu\right) + k_\nu\left(\frac{B_\nu}{c} - \mathsf{E}_\nu\right)$$

for the spectral radiation energy density $\mathsf{E}_\nu = \mathsf{E}_\nu(t,\vec{x},\nu)$; the coupling term to the fluid is

$$Q_r(t,\vec{x}) = \int k_\nu\left(c\mathsf{E}_\nu - B_\nu\right)\, d\nu \ .$$

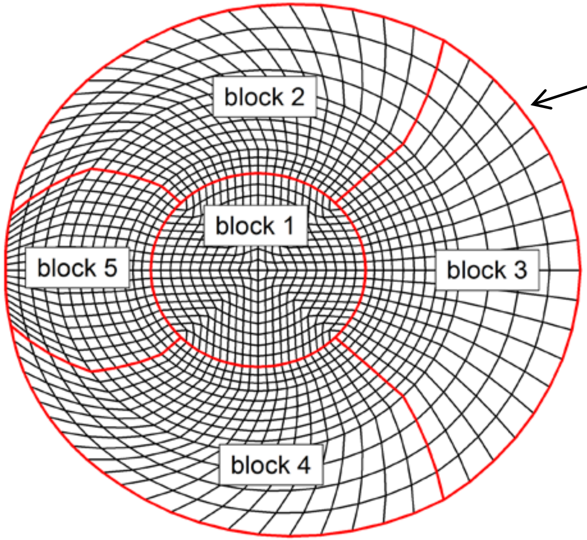
Here the information about ***<u>the angular dependence</u>*** *of the radiation field is lost; one simply has to solve some 30 – 100 additional mutually independent diffusion equations.*

<u>Not much of a challenge</u> for computational physics: there already exist numerically stable, <u>positive</u> and <u>conservative</u> numerical schemes on distorted (non-rectangular) grids.

In the RALEF code we have such a scheme implemented for the thermal conduction.

Adaptive mesh

RALEF uses quadrilateral <u>adaptive</u> mesh composed of separate blocks, each of which is topologically equivalent to a rectangle.

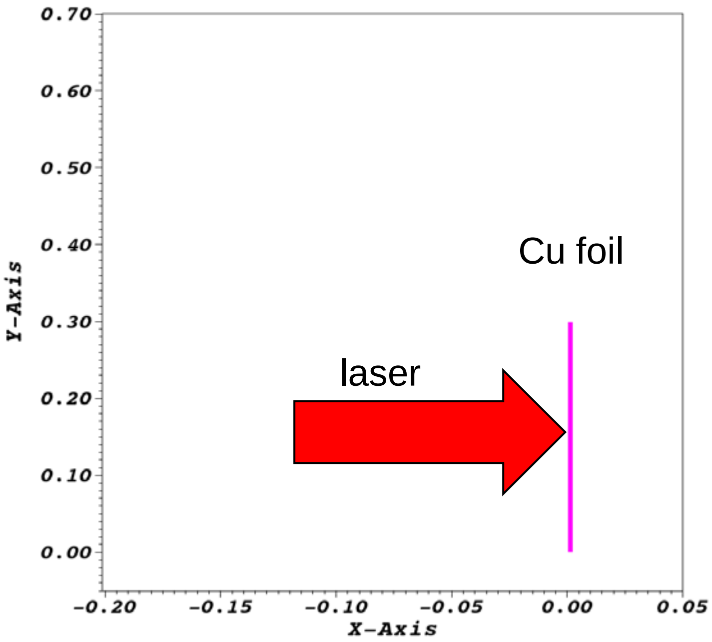


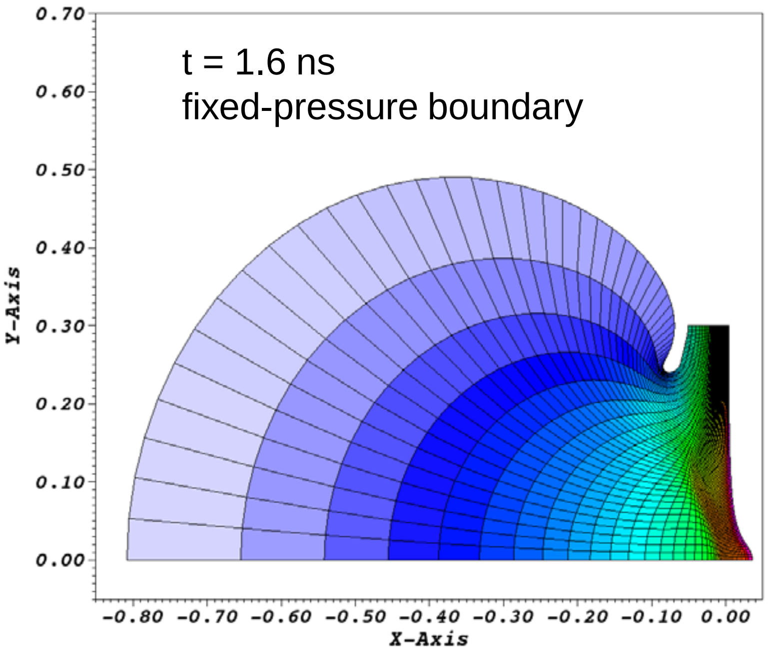
Type of mesh used to simulate laser-irradiated spherical droplets of tin.

Mesh adaptivity is realized by implementing the Arbitrary Lagrangian-Eulerian technique, which allows free motion of the (x,y) [or (r,z)] mesh – independent of the motion of the fluid!

Limitations of the ALE technique

Example: laser irradiation of a Cu foil

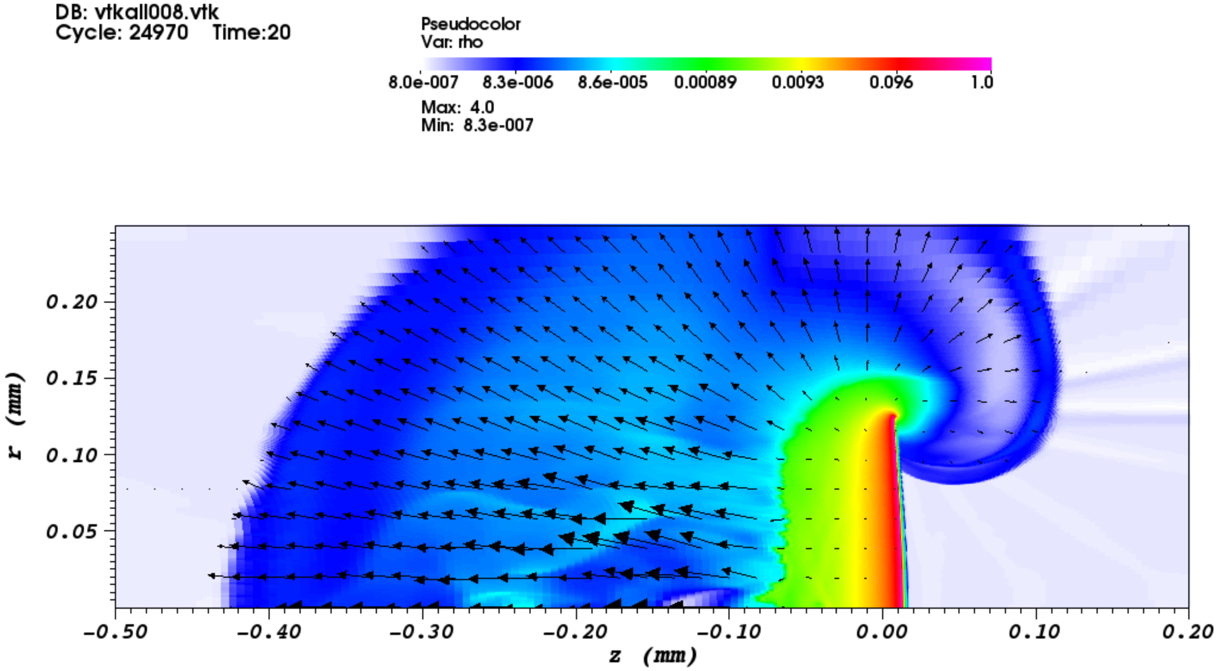




Simulation stops because a singularity develops at the plasma-vacuum boundary !

Flexible boundary conditions

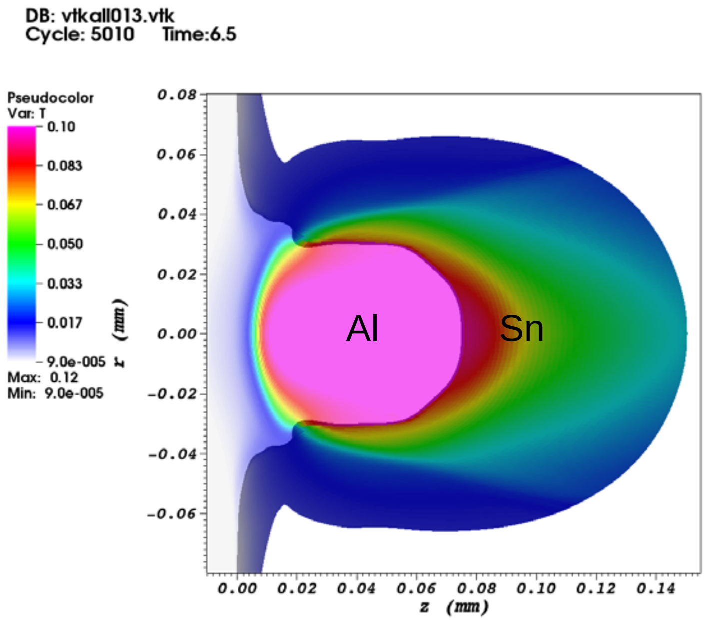
Laser irradiation of a thin Sn disk:



Limitations due to different materials

By finding an appropriate combination of boundary conditions and ALE options, one can adequately simulate practically any 2D problem with a single material.

Multiple materials pose an additional challenge:



In RALEF, mixing of different materials within a single mesh cell is not allowed $\Rightarrow$ hence, any material interface must be treated as a Lagrangian curve (surface), which usually tends to get folded and tangled: as a result, the simulation stops!

Opacity options in RALEF

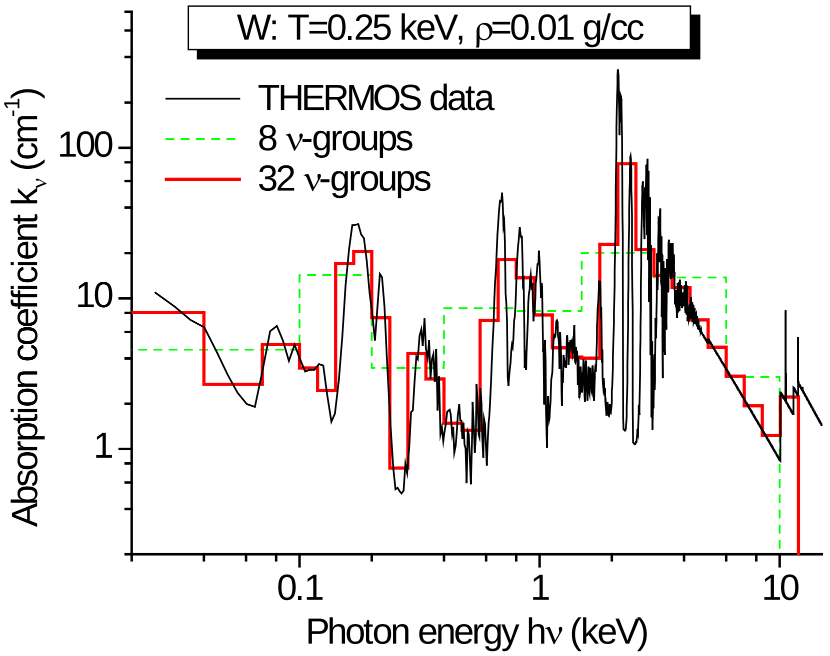
Here we profit from many years of a highly qualified work at KIAM (Moscow) in the group of Nikiforov-Uvarov-Novikov (the THERMOS code based on the Hartree-Fock-Slater atomic modeling).

Opacity options:

1. power law,
2. ad hoc analytical,
3. inverse bremsstrahlung (analytical),

   . . . .

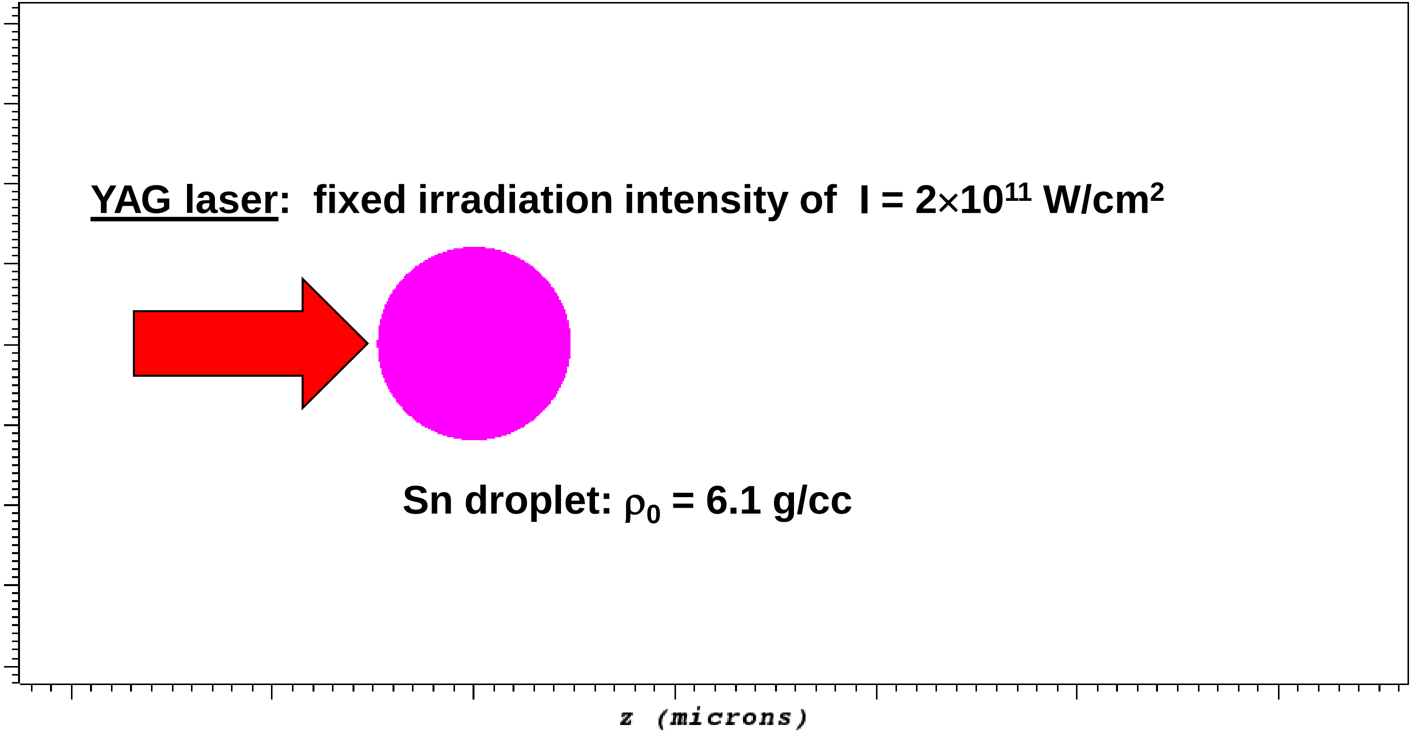
7. Opacity tables based on the THERMOS data

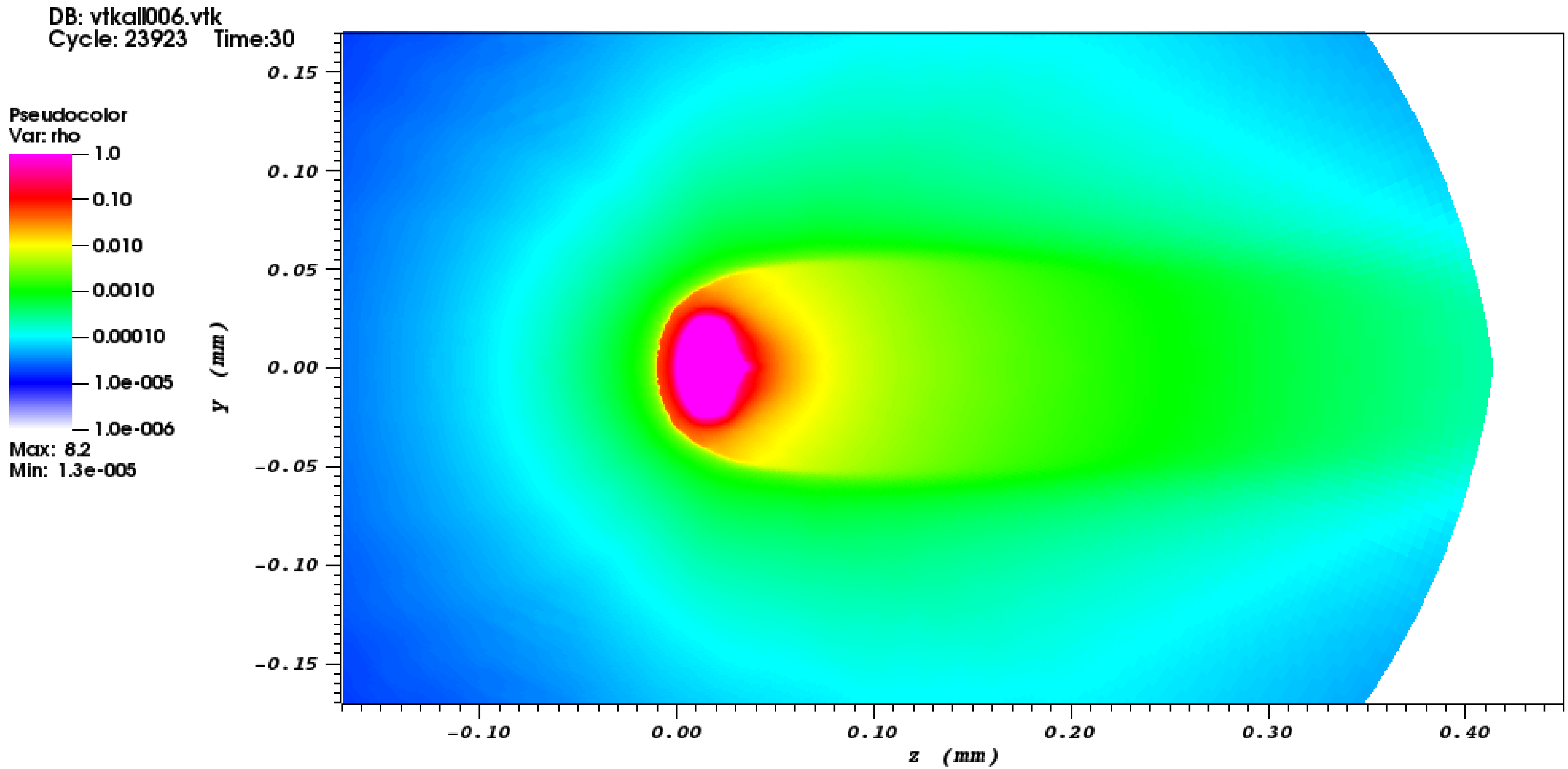


Illustrative roblem # 1:

ablation of a Sn droplet by a YAG-laser pulse

Sn droplet under a constant flux from YAG laser

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Cycle: 23923 Time:30
Pseudocolor
Var: rho
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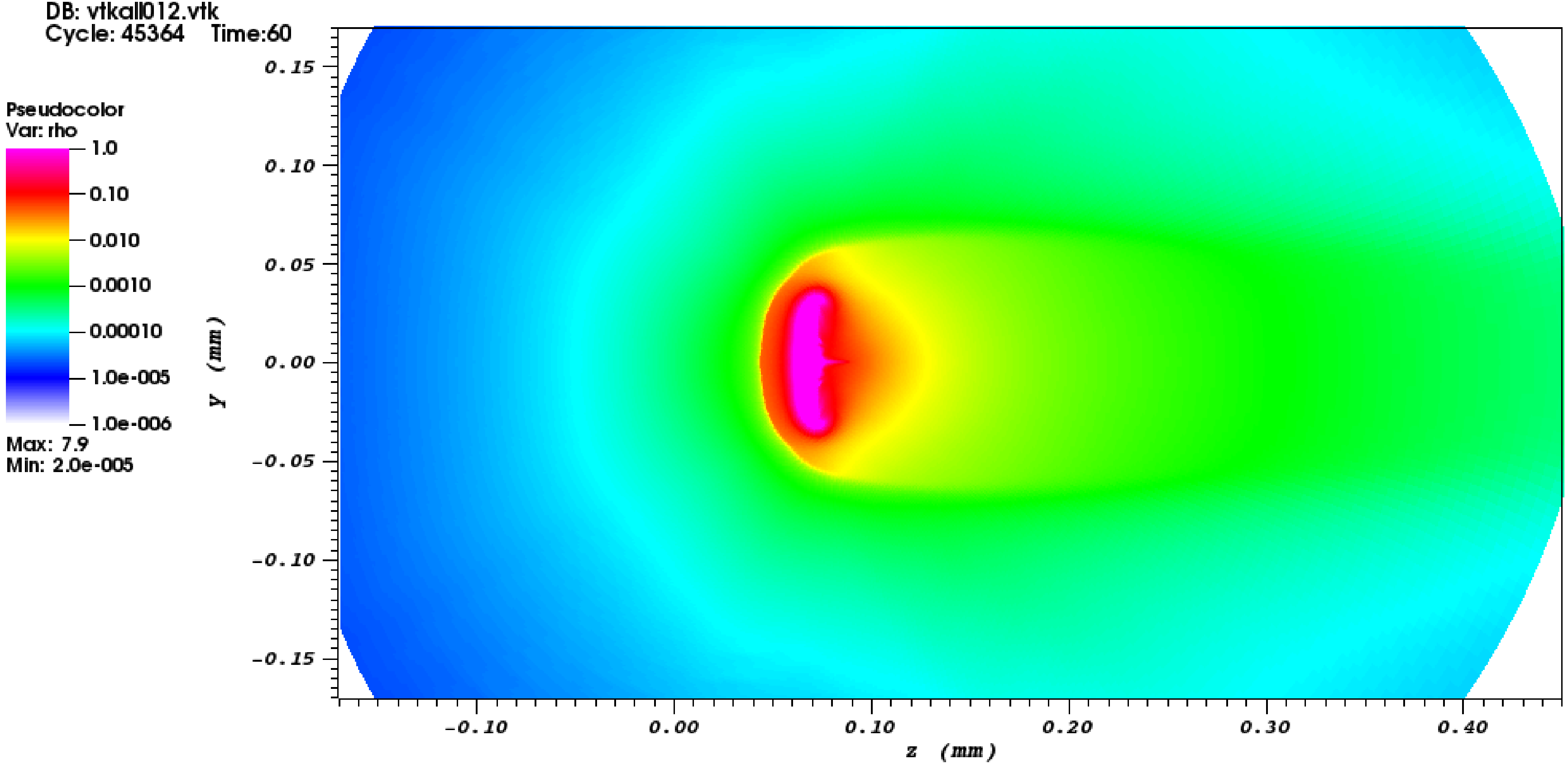
0.10
0.010
0.0010
0.00010
1.0e-005
1.0e-006
Max: 8.2
Min: 1.3e-005
0.15
0.10
0.05
0.00
-0.05
-0.10
-0.15
y (mm)
-0.10
0.00
0.10
0.20
0.30
0.40
z (mm)



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Cycle: 45364 Time:60
Pseudocolor
Var: rho
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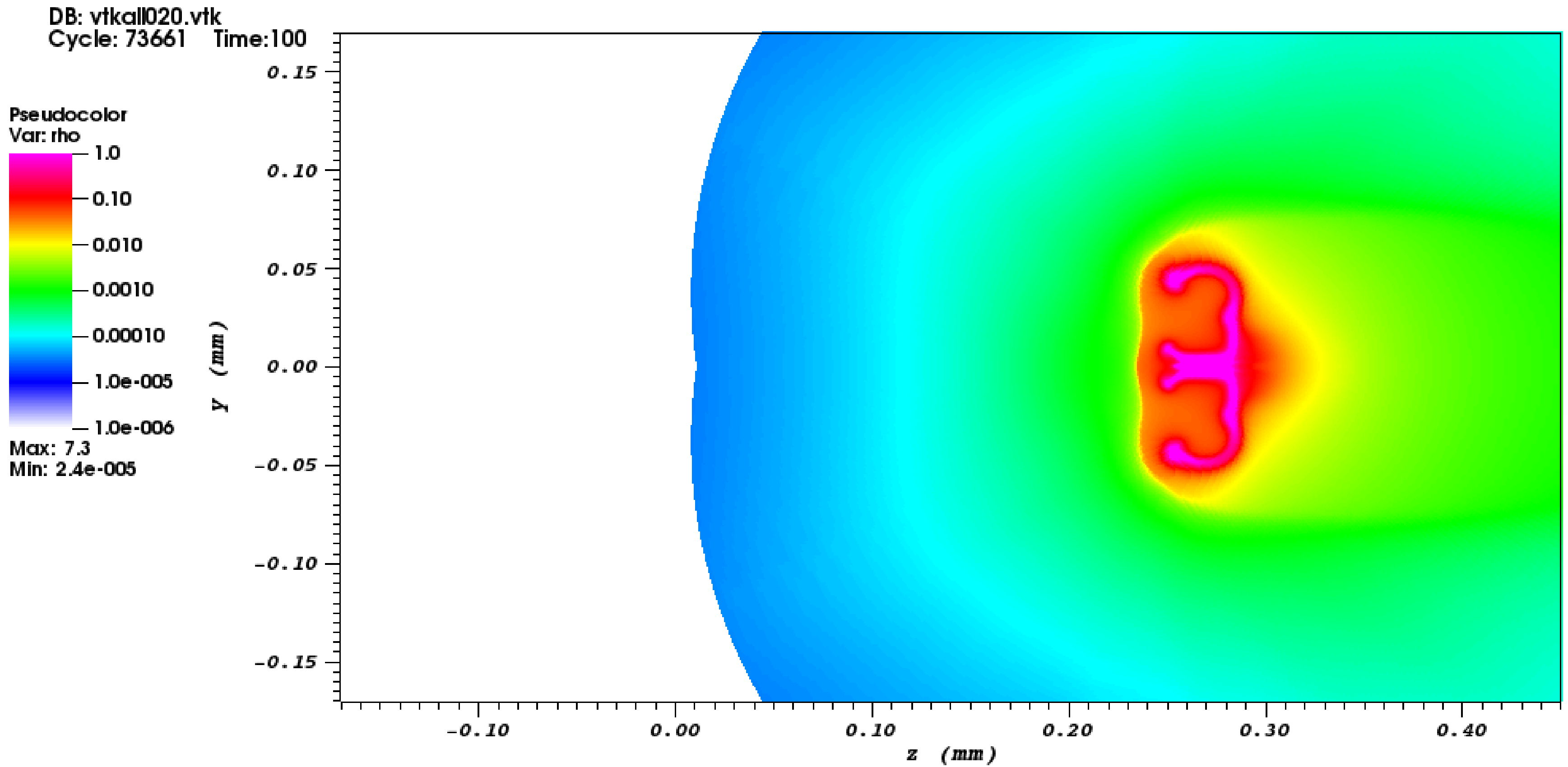
0.010
0.0010
0.00010
1.0e-005
1.0e-006
Max: 7.9
Min: 2.0e-005
0.15
0.10
0.05
0.00
-0.05
-0.10
-0.15
y (mm)
-0.10
0.00
0.10
0.20
0.30
0.40
z (mm)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Cycle: 73661 Time:100
Pseudocolor
Var: rho
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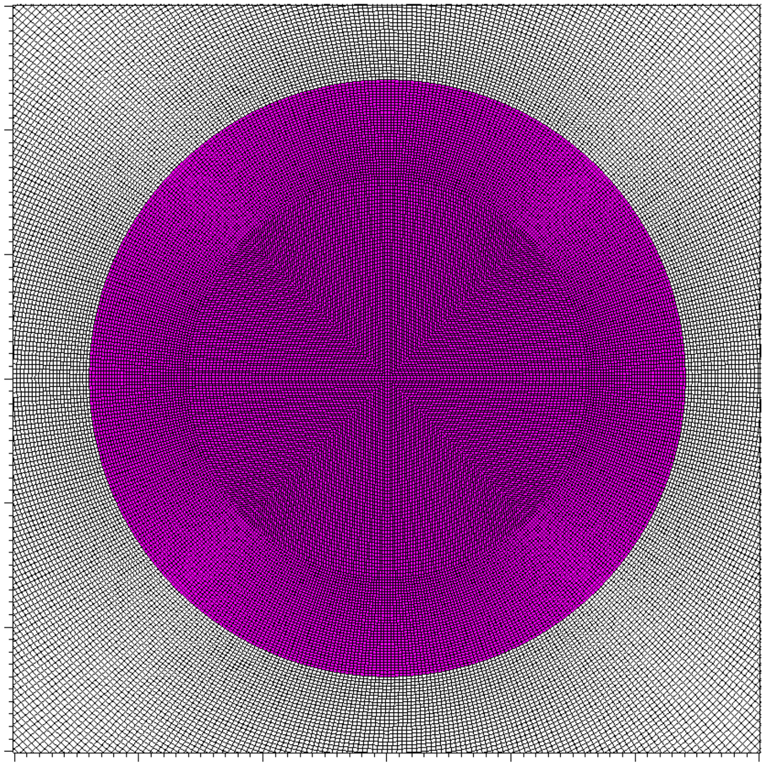
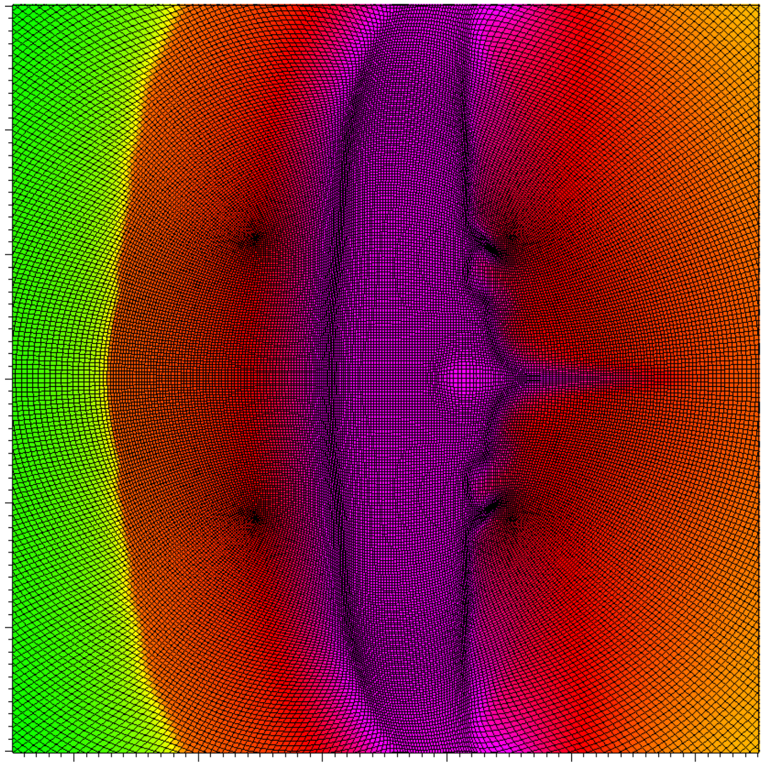
0.10
0.010
0.0010
0.00010
1.0e-005
1.0e-006
Max: 7.3
Min: 2.4e-005
0.15
0.10
0.05
0.00
-0.05
-0.10
-0.15
Y (mm)
-0.10
0.00
0.10
0.20
0.30
0.40
z (mm)

Mesh evolution

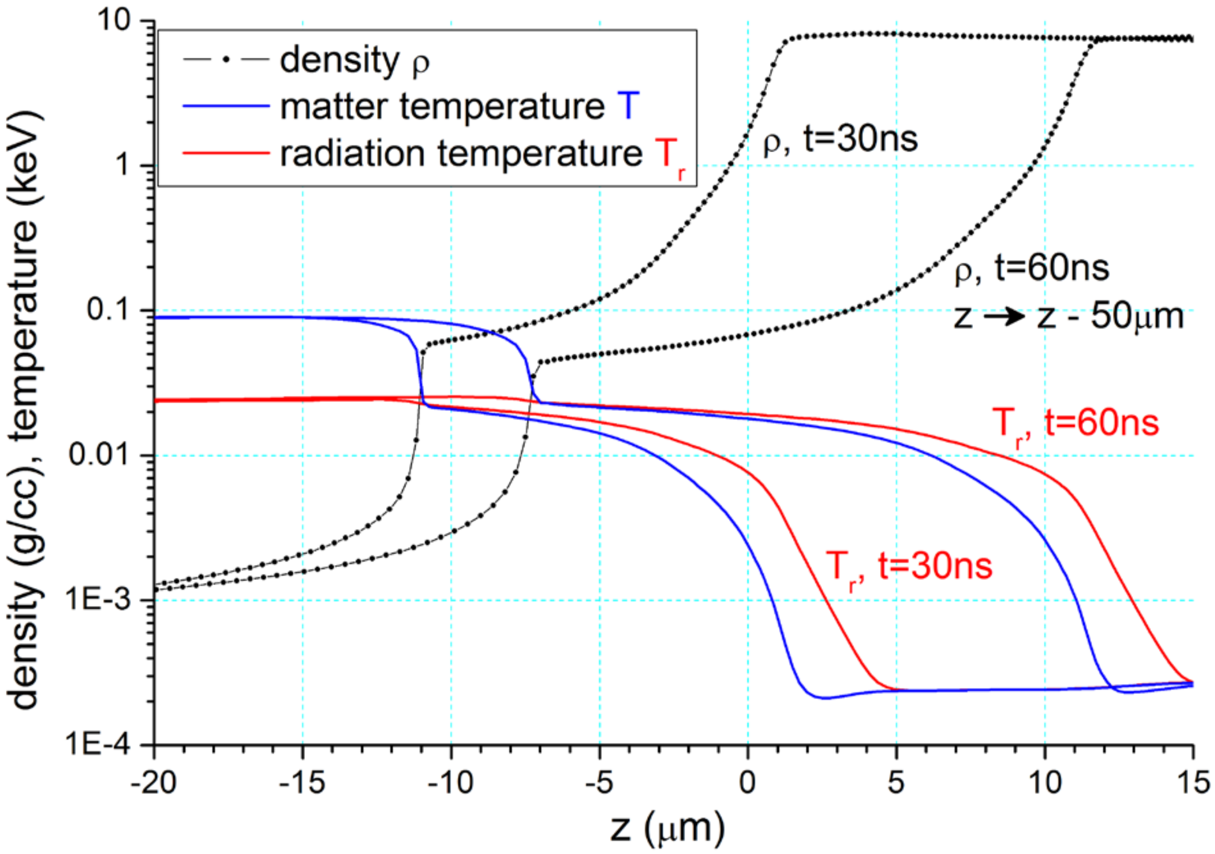
t = 0



t = 60 ns



Temperature and density profiles across the ablation front



Physics of the radiation-dominated laser ablation front

For high-Z targets (like Sn droplets), the energy transport by thermal radiation plays an important role in shaping the plasma flow across the laser-driven ablation front and, for that reason, has a strong effect on the mass ablation (evaporation) rate.

The structure of a quasi-steady radiation-dominated (RD) ablation front can be approximated as

- a deflagration-type discontinuity of the hydro flow at the critical surface, followed by
- a radiation-diffusion thermal wave (a Marshak wave) propagating into the cold unablated material.

By matching the boundary conditions for these two types of thermo-hydrodynamic structures, one can evaluate the mass ablation rate.
The ablation rate, calculated without radiation energy transport – i.e. with only the electron thermal conduction, turns out to be underestimated by a factor 2-5.

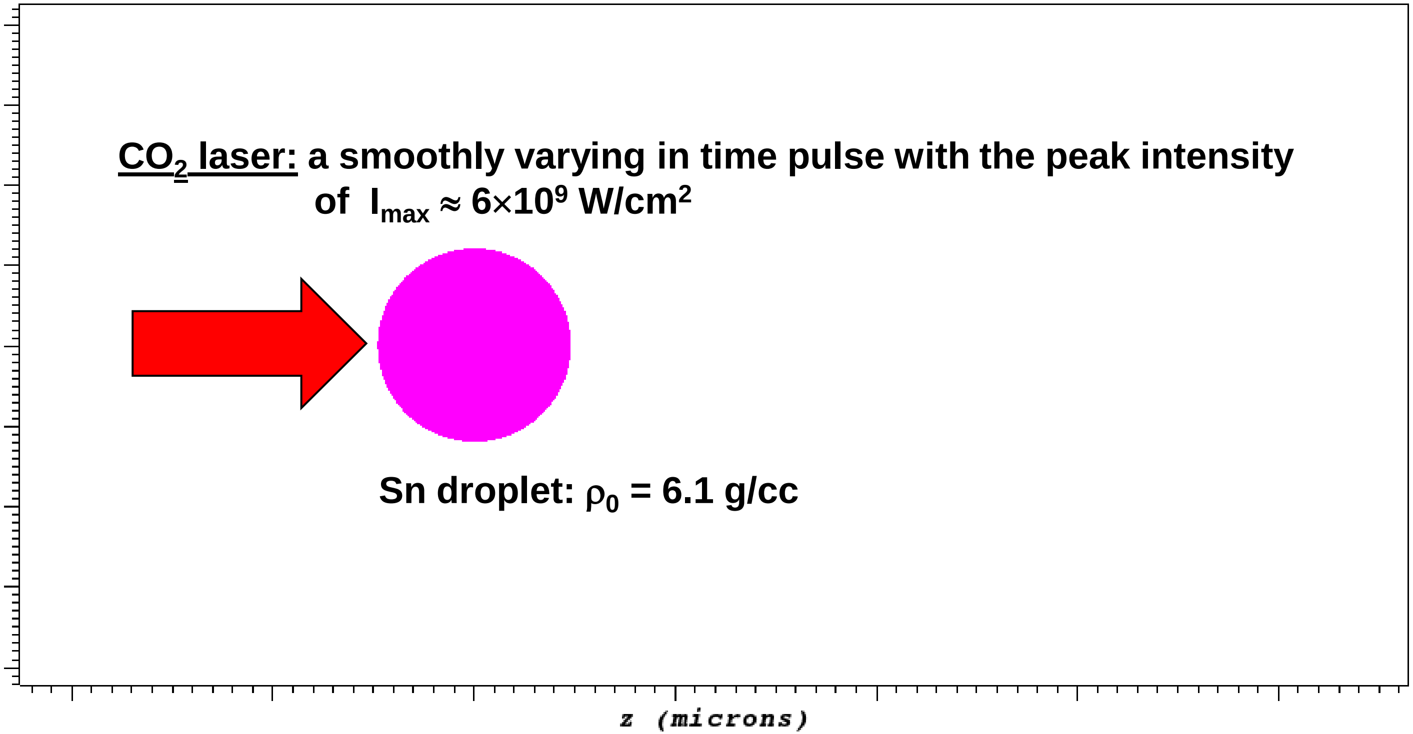
For a fixed incident laser flux, the structure of the ablation front is not quite steady-state because of slow evolution in time of the diffusive RD thermal wave.

Illustrative problem # 2:

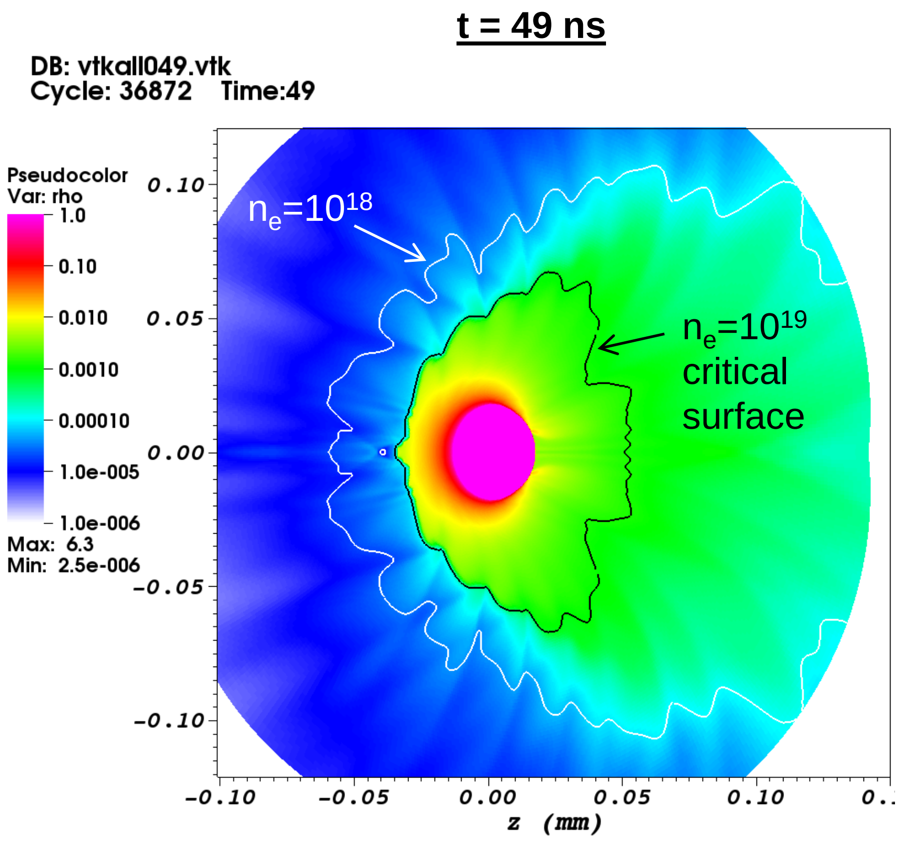
flattening of a Sn droplet into a thin disk

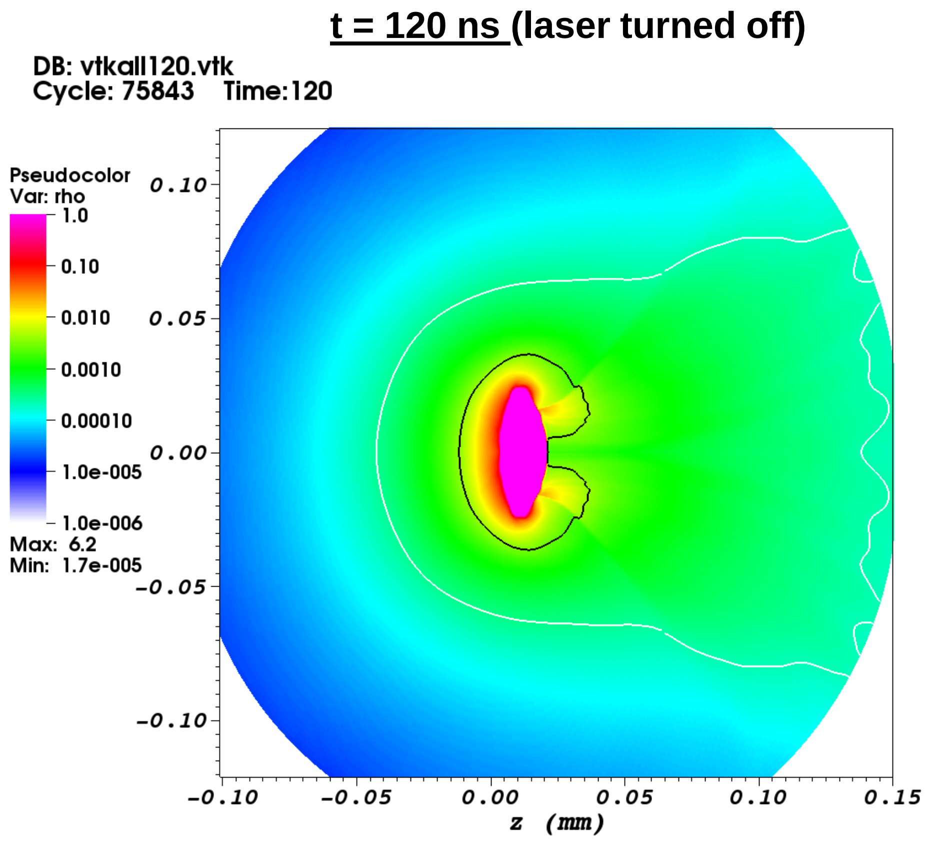
by a CO_2-laser pulse

Sn droplet under CO_2 laser irradiation



2D color maps of plasma density





Impact of hydrodynamic instabilities

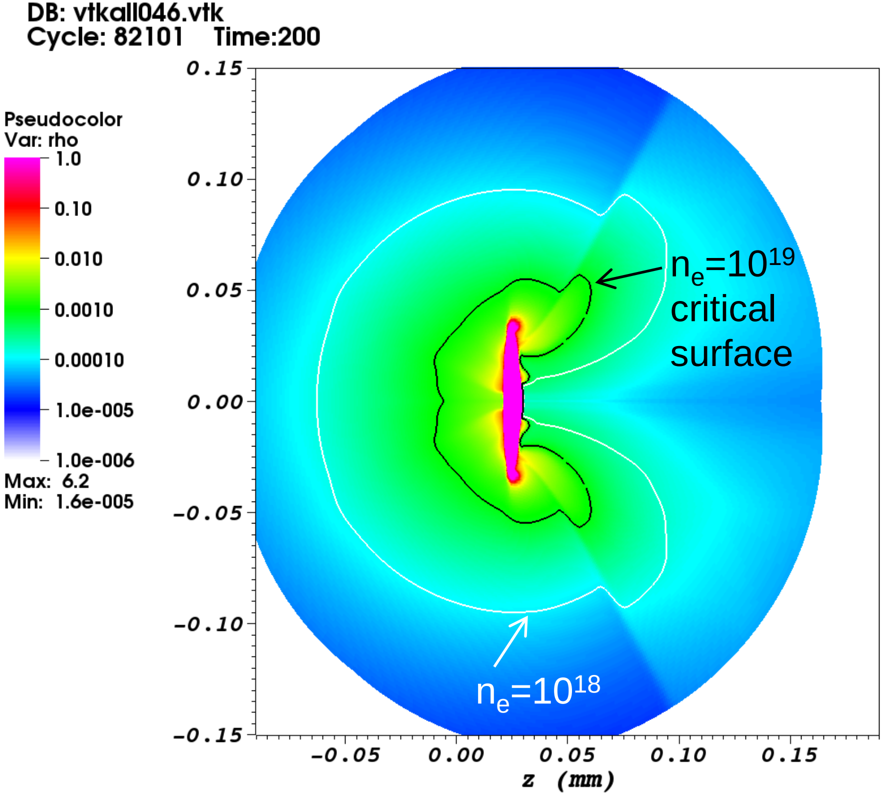
- The critical surface around a Sn droplet, where the gradient of the plasma density is very steep, is subject to the Rayleigh-Taylor and Kelvin-Helmholtz hydrodynamic instabilities.

- Strong non-linear perturbations from the critical surface feed through the “cushion” of diffusive thermal wave into the bulk of the liquid Sn – which might preclude quasi-planar flattening of the droplet into a thin (sub-micron) disk of liquid Sn.

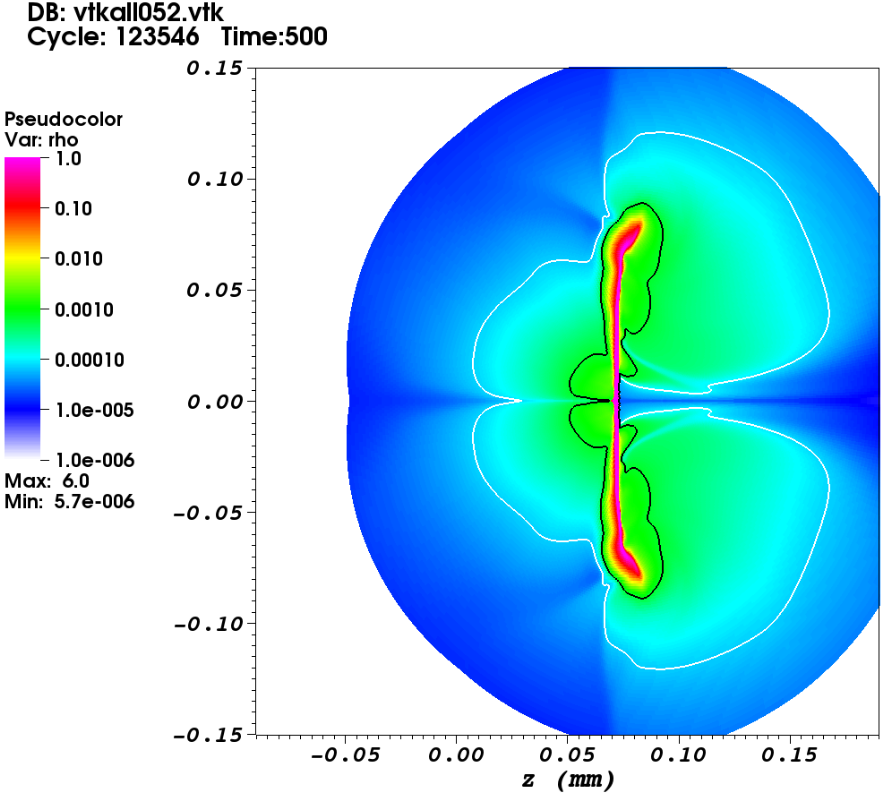
- However, due to dominant role of thermal radiation (with the mean free path on the order of 1–10 microns) in the energy transport through this layer, the perturbations from the critical surface are strongly suppressed and rendered relatively harmless for the process of droplet flattening.

Liquid droplet evolution after laser turnoff

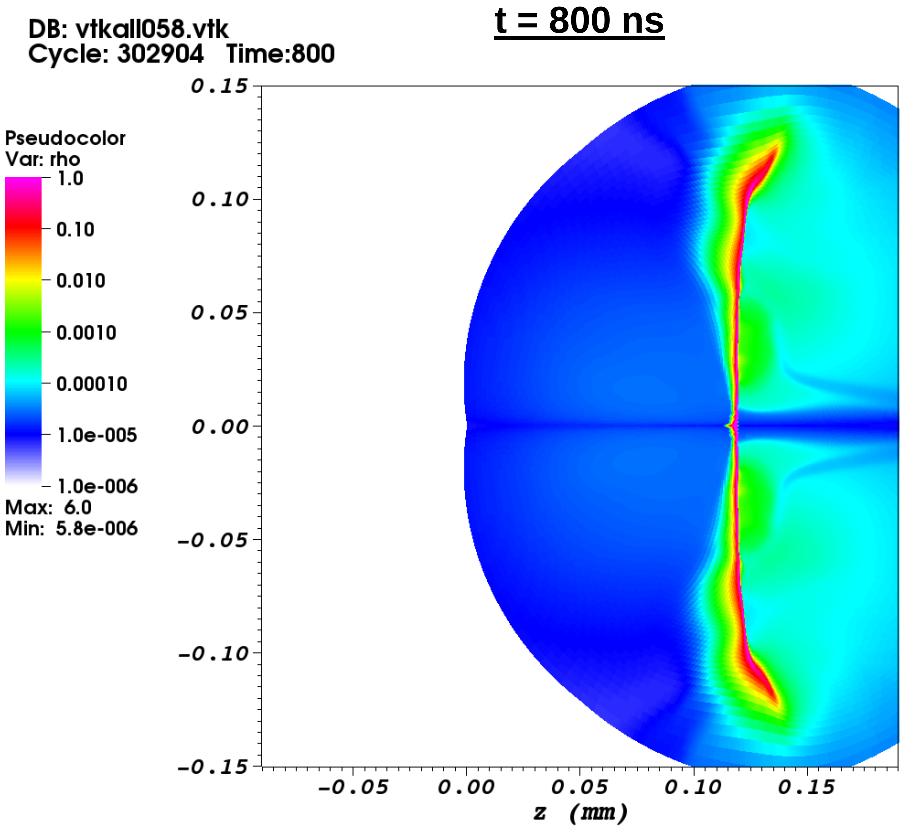
t = 200 ns

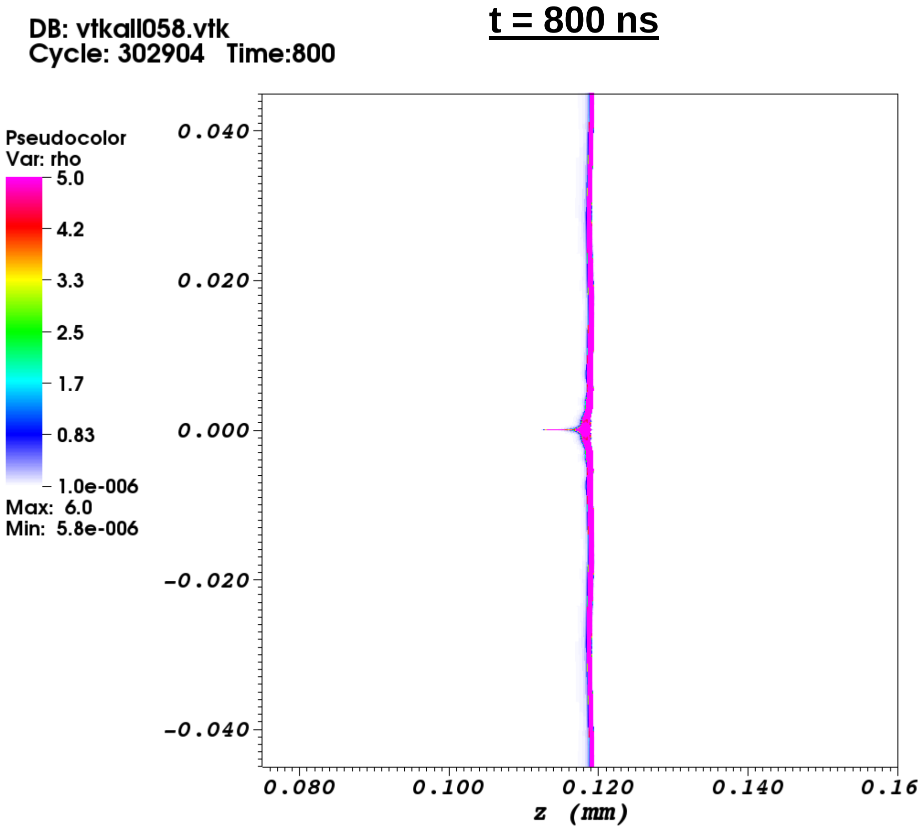


t = 500 ns

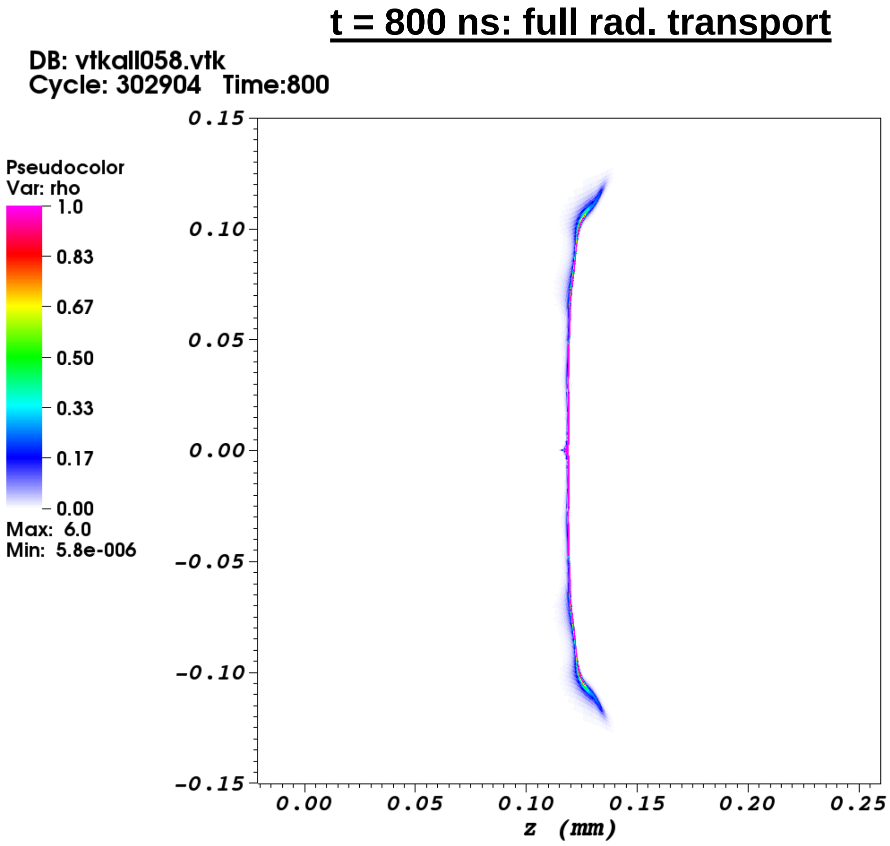


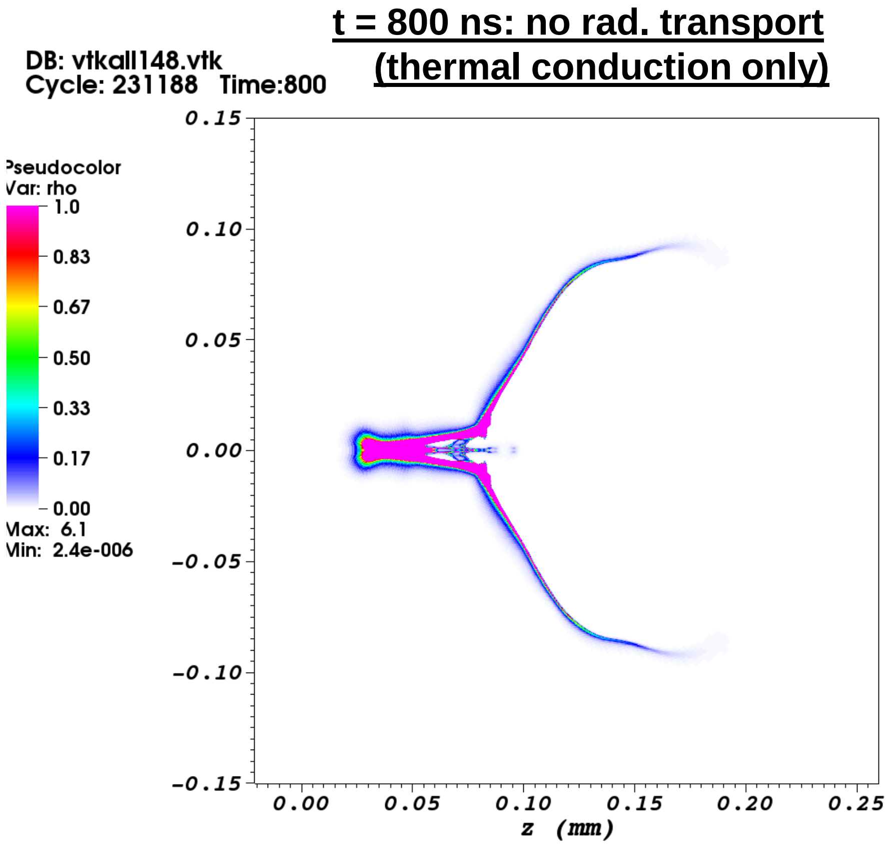
Shape of liquid Sn at t = 800 ns





Comparison with turned off radiation transport





Conclusion

- Adequate modeling of the hydrodynamics of laser irradiated Sn droplets, used as targets for generation of the 13.5-nm EUV emission, requires the equations of 2D (3D) hydrodynamics to be coupled with the simultaneous solution of <u>the spectral transfer equation</u> for thermal x-rays – even at laser intensities as low as few by 10^9 W/cm^2.

- The radiation energy transport – under the discussed conditions – proves to be the key factor
  - for determining the mass ablation rate (hence, the ablation pressure), and
  - for suppressing the feed-through of the hydrodynamic instabilities